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Numerical Analysis of a Two-Layer Dynamic Thermal Stratification Model for Saveh Lake in Iran

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ABSTRACT

To examinethe thermal stratification of Saveh dam reservoir a two-layer model was developed and its differential equations were solved using Runge-Kutta numerical method. The influences of inflow temperature and solar radiation in the reservoir temperature were examined by a sensitivity analysis. In the first case the inflow temperature to the reservoir increased by 60% and then decreased by 40%. In the second case ±20% changes of solar radiation was applied to the model.Comparingthe simulatedvaluesby themodeland themean of measuredvaluesin the dam reservoir above and below thermocline layer proved that the model has acceptable results for predicting surface and deep water temperature (R^2 was 0.98).Results indicated that inflow temperature changes are synchronized with reservoir temperature, but solar radiation changesaffectedsignificantlythetemperature of thewater in the reservoir.Depending on the value of changes employed, the solar radiation caused more than ±13% change in the surface water temperature and more than ±10% change in the bottom water temperature. Moreover, depending on the value of changes employed, the inflow temperature caused less than ±11% change in the surface water temperature and less than ±7% change in the bottom water temperature.Numerical analyses indicated that 60% of times during annual year the reservoir shows thermal stratification. Consequently, in January, February, March and April, there was no perceptible stratification in the reservoir while in May, June, July, August, and late September stratification in reservoir was considerable.

KEYWORD

Thermal stratification, SavehLake, A two-layer model, Runge-Kutta method, Sensitivity analysis.

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INTRODUCTION

Populationgrowth and human development, has focused researchers and water resources planners to have much more attention to the water quality and local environment issues[1, 2].Building a dam to supply water is one of the solutions for decades [3]. Nowadays great importance is given to water pollution and environmental impact upon reservoirs[4]. Dam construction isone of thefactors affecting water quality and its effect is due to cause thermal stratification and retention time. [4-6]. These two factors can cause drastic changes in water quality output to the reaching streams.Therefore, reservoirs in addition to providing water, they are controlling water quality changes too [7].

Thermal stratification phenomenon is mostly concentrated in air or liquid medium. Although temperature stratification of indoor air is studied in many literatures [8, 9], more applications are combined with water supply system, especially in solar engineering. The research on thermal stratification within the tank has been studied intensively since 1970s [10]. simulations of thermal stratification in storage tank were performed by a number of researchers, whose studies showed, thermal stratification can effectively improve the performance of the energy storage [11]. Furthermore, thermal stratification is one of the most important environmental issues for deep waters due to its strong effects on physical, chemical, and biological processes [12]. Often in summer, surface water temperature is much higher at Lake Bottom, consequently, water densities become stacked vertically, forming the upper layer epilimnion, the bottom hypolimnion, and thermocline between them. Note that the thermocline can be regarded as a transition layer with a sharp temperature gradient [13, 14]. Vertical stratification causes weak mixing, which in fact prevents the surface water from supplying substances to the bottom layer. Therefore, nutrients and Dissolved

Oxygen (DO) are often confined only in the epilimnion layer, causing a series of water quality problems such as hypo-xia [15, 16].

Thermal stratificationalsoisthe mostimportant phenomenon that cause reservoirs to have seasonal changes in water quality [17, 18]. This phenomenon can cause adverse effects on water quality of the reaching streams. Severe changes in temperature, density, salinity and depth of the reservoir, reducing dissolve oxygen concentration, unpleasant odor and flavor due to high concentration of Fe and manganese in the water and hydrogenated gas output, are including the effects of thermal stratification within the lake behind the dams [19, 20].

Theinitial purpose of predicting flow in stratified reservoirs is calculating temperature distribution and heat and mass transfer in the reservoir [21, 22]. Precision in simulation, is affecting values of parameters of water quality such as dissolved oxygen [23, 24]. Earlier studies on the effects of mixing flow in reservoir stratification of Manson climate condition proved that the input water temperature throughout normal raining year is more important but during dry years the influence of this parameter is very low [25].A hydrodynamic model was applied to quantify the way in which the thermal regime and hydrodynamics of a large and stratified reservoir would respond to changes in local climate and hydrological conditions. The model simulations were conducted to study the onset/end time of stratification, surface and outflow temperature, thermal stability, and assess the impacts of probable external changes on the ecosystem to gain an understanding of the thermal regimes of reservoirs in southern China. The simulations indicated that the end of seasonal stratification is more sensitive to hydrological conditions than the onset, and that the outflow temperature is more variable in spring and early summer when the reservoir has the lowest water level [6].

In thecurrent research, we represented a two layer thermal stratified reservoir model for Lake of Saveh and Runge-Kutta scheme was applied to solve the set of differential equations.Furthermore, the results were introduced as temperature of surface and bottom layers of water. Following the study, a sensitivity analysis was performed to determine the influences of water temperature and solar radiation in the reservoir water temperature

MATERIALS AND METHODS

A) Case Study Area

Saveh Lake is situated in the Vaforghan Valley, about 25 km from Saveh city and 150 Km southwest of Tehran on the river of Ghare-Chai (Fig. 1). The lake is about 9 km^2 in area andits longitudeand latitude coordinationare 34° 53′ 52.01″ N and 50° 8′ ″31.99 E respectively.Its elevation is 1080 m above mean sea level. From 1995 to 2012 average annual precipitation was about 230 mm and average monthly temperature ranged from 30 °C during July to 4.9 °C during January. One medium stream drain into the lake and a dam regulates the outlet and maintains the lake at a higher and more stable stage than would naturally occur. The purposes of constructing Saveh dam are as follows: 1. Regulating river flow and flood control 2. Irrigating of 23000hectaresoflowland in Saveh 3. To providedrinking watersupplyandwater for Saveh and Kavehindustrial park, 4. And to produce fifteenmegawattselectricity.

Fig.1. Natural plan and location of Saveh Lake in Iran.

B) Reservoir Stratification

A phenomenon that has a considerable effect on the water quality in reservoirs is thermal stratification [26]. Accurate assessment of this phenomenon and investigating its effects on water quality in reservoirs can enable us to usethisnaturalphenomenon for improving water quality in reservoirs [6, 27].Watertemperature has considerable effects on decompositionoforganic materials and accelerating chemical reactionof chemical compounds. Furthermore, temperature influences the concentrations and process of changes of governing factors, which can determine water quality in reservoirs [21, 28, 29].

Asubstance whetherchemical or biochemical in a reservoir is dispersed by conductionand dispersion due to turbulence [30]. In addition, the substance is influenced by numerous chemical, biochemical and physical processes [31]. Havingacomprehensiveunderstandingfrom thedistributionofchemicaland biochemicalprocessesesis essentialforpredictingwater quality [29, 32]. Stratification is supposed to introduce layersoffluidthat iscaused as aresult ofdifferencesindensityortemperature, or dissolvedandsuspendedmaterials. In several reservoirsand lakes, Stratification is thermalequilibriumbetweenwaterandotherinputsto thereservoir [33, 34].

(Fig. 2) shows three specified layer that could occur during the stratification [35] including, 1) Surface layer or epilimnion, which is the areas with the higher temperature, warmer and with lower water density. This layer is a thin layer with uniform temperature. The thickness of this layer is difference by lake to lakes and month to months [30, 35]. 2) Lower reservoir layer or hypolimnion, is the lower and cooler area with higher water density. The cold 4 °C water with lower thermal gradients is located at the bottom of the reservoir. Presence of heavier, colder water, with lower dissolve oxygen in water reservoir could makes drastic changes in water quality [11, 14]. 3) Middle layer or metalimnion, the region between the surface layer and lower layer which is called thermocline is located at this layer. There isa sharpgradientof densityand temperature in the

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middle layer that would causeexclusive verticalheat andmomentumtransferinthelake. And also has caused separationof hydraulic, thermalandecological characteristics of two layers in the lake [14, 30].

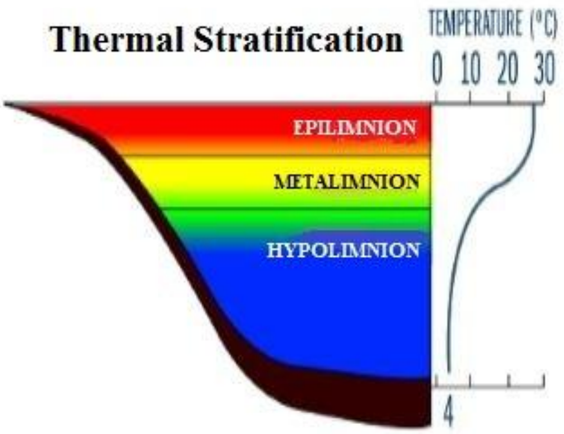

Fig. 2. Schematic configuration of a three-layer thermal stratification model

C) Mathematical Modeling of Thermal Stratification

One way todealwithwater quality issues and water resource management is to analyze the water temperature of reservoirs.Different types ofmathematicalmodels could increase the understanding of thermal issues [17]. Thesemodelsincludea set ofconcepts which have obtained with passing of time. At a result ofusing them is developingtechniquestosolvepractical problems. These models usually make up from a smallset ofmodels, thereby increasing thecomplexity of amodel and all the times could not be beneficial [26]. Although many one- dimensional models applied in the vertical direction at one location in a water body are able to simulate fairly the temperature dynamics in stratified lakes, simulations for morphologically complex reservoirs such as the Saveh usually require the use of multi-dimensional models [36]. The Saveh has abrupt spatial variations in area and depth that cannot be adequately modeled using a one-dimensional vertical model. (Fig.3) shows the two layers thermal stratification modelusedin this study, whichthelower surface layer isassumed to be negligible.

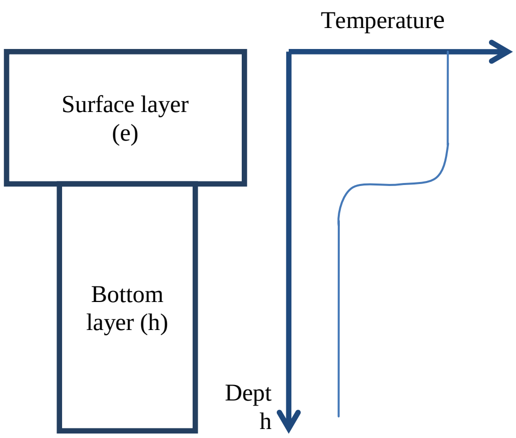

Fig. 3. Schematic configuration of a two-layer thermal stratification model

The present research focused on using the temperature distribution in lake as a main influencing factor.The model is due to directly predict the temperature distribution in Saveh Lake. The relation between the temperatures in the water model and the temperatures in the reservoir can be expressed mathematically as:

$$\text{Accumulation} = \text{Inflow} - \text{Outflow} \pm \text{Surface heat exchange} \quad (1)$$

$$V_h\,\rho\,C_p\,\frac{dT_h}{dt} = Q_{in}\,\rho\,C_p T_{in}(t) - Q_{out}\,\rho\,C_p\,T_e + J_{sn}A_s + (A + 0.031\sqrt{e_{air}})(1 - R_L)A_s - \epsilon\sigma(T_e + 273)^4 A_s - c_1 f(U_w)(T_e - T_{air})\,A_s - f(U_w)(e_s - e_{air})A_s + v_t\,A_t\,\rho\,C_p(T_h - T_e) \quad (2)$$

$$V_h\,\rho\,C_p\,\frac{dT_h}{dt} = v_t\,A_t\,\rho\,C_p(T_e - T_h) \quad (3)$$

Where, h is surface layer parameter index, e is bottom layer parameter index, V_h is surface layer volume, Q_{in} isinput discharge, C_p is waterspecificheat , ρ is water density, J_{sn} is netsolarradiationshort-wave, A_s is thereservoirarea, σ is Stefan-Boltzmann constant, A is the coefficient between 0.5 to 0.7, e_{air} is airvapor pressure, R_L is reflectioncoefficient, ∈is ability ofwaterwave propagation, c_1 is Bowen ratio, $f(U_w)$is transfer function of wind and e_s is vapor pressure in saturation mode.

D) Numerical Solution Method in Runge-Kutta Domain

In numerical analysis, the Runge-Kutta methods are an important family of implicit and explicit iterative methods, whichareused in temporal discretization forthe approximation of solutions of ordinary differential equations[37]. In contrast to the multistep methods of the previous section, Runge-Kutta methods are single-step methods, however, with multiple stages per step. Each Runge-Kutta method is derived from an appropriate Taylor method.A trade-off is made to perform several function evaluations at each step and eliminate the necessity to compute the higher derivatives. These methods can be constructed for any order N. The Runge-Kutta method of order N equal to 4 is most popular [38]. It is a good choice for common purposes because it is quite accurate, stable, and easy to program. Most authorities proclaim that it is not necessary to go to a higher-order method because the increased accuracy is offset by additional computational effort. If more accuracy is required, then either a smaller step size or an adaptive method should be used [39]. Runge-Kutta method (RK) is one of the numerical solution methods are widely used in water quality modeling. One of themost commonmethodsofRK, which consists fourstepsas follows:

$$T_{i+1} = T_i + \left[\frac{1}{6}\,(k_1 + 2k_2 + 2k_3 + k_4)\right] h \; (4)$$

$$k_1 = f(t_i\,, T_i) (5)$$

$$k_2 = f\left(t_i + \tfrac{1}{2}h\,,\; T_i + \tfrac{1}{2}hk_1\right) (6)$$

$k_3 = f\left(t_i + \frac{1}{2}h\,,\; T_i + \frac{1}{2}hk_2\right)$(7)

$k_4 = f(t_i + h\;,\; T_i +\; hk_3)$(8)

$f(t, T) = \frac{dT}{dt}(t, T)$(9)

E) Dam Reservoir Data's Used in the Study

Data used in this study is related to 11 months from January of 2012 to September of 2012. Thisinformation includessolarradiation, air temperature, inletWatertemperature, input, output rate, estimatethe amountof wind, depthestimationof thermocline.General physical characteristicsof thereservoirarealsoshownin(Table. 1)Numerical analyses of observed data were established based on the theory of Runge-Kutta method, namely Runge-Kutta method of order 4 using the mathematical software program Matlab and Microsoft office excel program.

Tab. 1. General physical features of Saveh dam reservoir

Characteristics	value
Type of dam (concrete)	Twoarched
Maximum altitude	128 m
Averageusefulreservoirvolume	230 E+6 m^3
Average annual input	238 E+6 m^3
Averageadjustedwater	120 E+6 m^3
Surface layer volume	60 E+6 m^3
Bottom layer volume	60 E+6 m^3
Average depth of reservoir	56 m
Average depth of thermocline	16 m

RESULTS AND DISCUSSION

A) Results of a two-layer modeling

A two-layer numerical model has been solved with Runge-Kutta method. The results showed that the reservoir was stratified approximately during some months in the simulation year. Sinking water in a Lake pushes the bottom water towards the surface and mixes the water in the Lake, which causes lake-turnover.(Fig. 4) shows the annual pattern of mixing in Lakes.

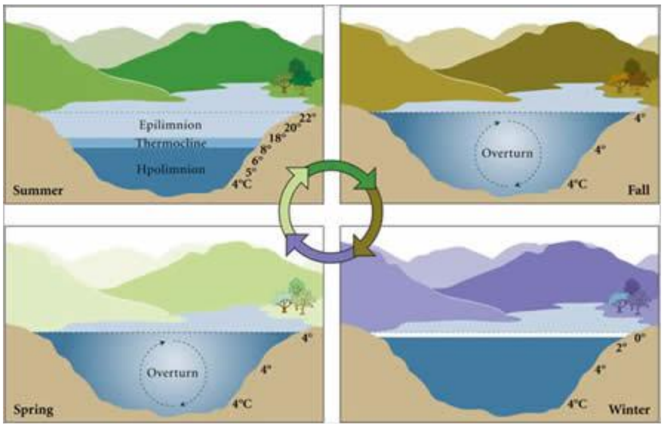

Fig. 4. Configuration of annual pattern of mixing in Lakes [13].

As fall gradually progresses into winter, the lake water remains at a fairly consistent temperature from top to bottom. The temperature range is very small, but important. The less dense water freezes on the surface at 0°C, forming ice. The water actually becomes warmer nearer the lake bottom. In a deep lake, the bottom water temperature is 4°C, the densest water. Ice and snow cover the lake during the winter forming an insulating blanket. In areas that do not experience much temperature change through different seasons, lakes mix year round, or several times a year with varying weather conditions [13, 15]. Spring turnover, the second of the two yearly turnovers, is the mixing of the entire water column. Several forces are at work in spring turnover. The sun, wind, currents, tributaries and groundwater all join together to mix the huge volume of water. As in fall turnover, nutrients are again mixed throughout the water column. This cycle repeats every year. Without this mixing, a lake can become stagnant, causing water quality to decline [13, 40].

The results of surface and bottom layer water temperature has been shown in (Fig. 5). As can be seen in January, there is no perceptible layering and temperature has changed between 10 to 12°C at reservoir body. In February reverse weak thermal stratification occurs. In bottom layer temperature has changed between 9 to 10°C and in surface layer it changes between 8 to 10°C. Starting April with a robust stratification. In May the temperature difference between the two layers are close to its maximum.Surface temperature has increased from 10 to 25°C and the lower layer from 10 to 11°C by November, but still there is stratification in surface temperature to reach a temperature of 15°C there. By November stratification still is continued, but surface temperature decrease to 15°C. As it's indicated in (Fig. 5) flowing water and air temperature changes are synchronized with reservoir temperature, but solar radiation changesaffectedsignificantlythetemperature of thewater in the reservoir.

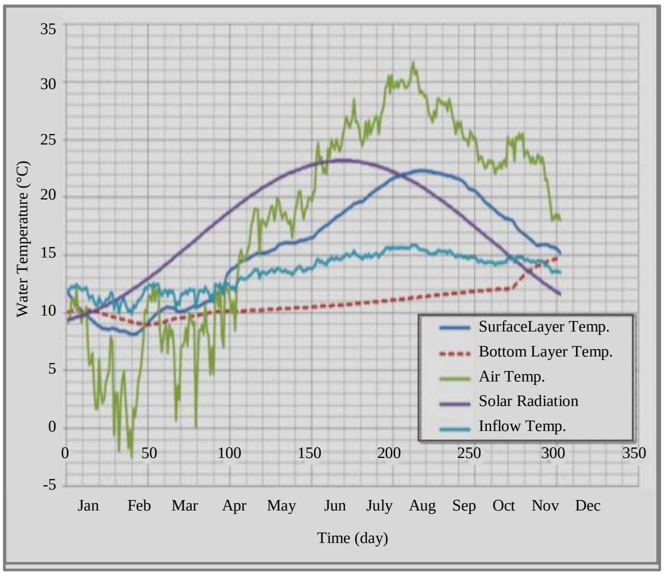

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Fig. 5. Temperature changes of surface and bottom layers of the reservoir from January to November.

It is important to examine the effects of flux on the reservoir temperature because when the upwards buoyancy flux due to the air bubbles is equal to the downward force on the entrained water, the bubble plume sheds the entrained water. In this way, the heavy bottom water is lifted up and mixed with the lighter water in the top layer. The bubble plume then begins to entrain the ambient water again, until it reaches the surface where any entrained water is shed. Continuation of this process mixes the water column thoroughly [41]. The results of different thermal flux input to and output to the reservoir are shown in (Fig. 6). The effects of inflow to the reservoir, solar radiation, atmosphere radiation, outflow, reflection, evaporation and condensation were invested in this study. The results show the flux in the month of April has increased greatly and then converges to zero. Furthermore, the changes of flux for other parameters is uniform, so they vacillate mildly over and under zero. Due to thelackof datafor the month of December, However,the resultsindicate that temperature in thetwo layersisconverged toward approachingNovember.

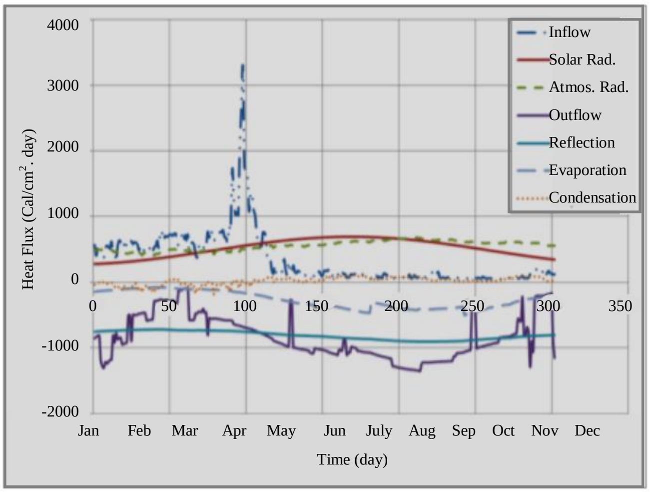

Fig. 6. Flux diagram of various effective factors on the reservoir temperature.

B) Results of Sensitivity Analysis

Sensitivity analysis and verification procedure proceeds to close disagreement between observed and simulated surface and bottom water temperatures. It was performed to disclose and highlight the most important variables affecting the epilimnion and hypolimnion temperatures. Short and long wave radiation, air temperature, wind speed vapor pressure, inflow temperature and light extinction coefficient were selected as the parameters to be investigated in earlier studies [14, 41]. To determine the influences of inflow water temperature and solar radiation in the reservoir water temperature a sensitivity analysis was performed in the current research. In the first case the inflow temperature to the reservoir increased by 60% and then decreased by 40%. In the second case 20% increase and then 20% decrease in solar radiation was applied to the model.

B, A) Analysis of Inflow Water Temperature

The results of sensitivity analysis to determine the effect of changes of inflow temperature on the temperature of reservoir(surface and bottom layers) are shown in (Fig. 7). According to the results by changes in the inflow temperature from March to June the surface layer temperature of reservoir has changed from 8.5 to 17°C. In other months this parameter has not a considerable influence. Under the case of 40% decrease in the inflow temperature to the reservoir, the simulated results matched adequately the measured profiles. As the 40% decrease in the inflow temperature caused 10.1% decrease in the surface water temperature. In addition, in the case of 60% increase in the inflow temperature to the reservoir, the simulated results matched the measured profiles well. The results showed that a 60% increase in the inflow temperature causes 10.6% increase in the surface water temperature.

The effects on bottom layer can be seen between the months of March to October (Fig. 7). The results showed that by changes in the inflow temperature from March to October the bottom layer temperature of reservoir has changed from 8.3 to 13°C. In other months this parameter has not a considerable influence. In the case of 40% decrease in the inflow temperature to the reservoir, the simulated results matched the measured profiles very well. As the 40% decrease in the inflow temperature caused 4.76% decrease in the bottom water temperature. In addition, under the case of 60% increase in the inflow temperature to the reservoir, the simulated results matched the measured profiles well. The results indicated that a 60% increase in the inflow temperature causes 7.14% increase in the bottom water temperature.

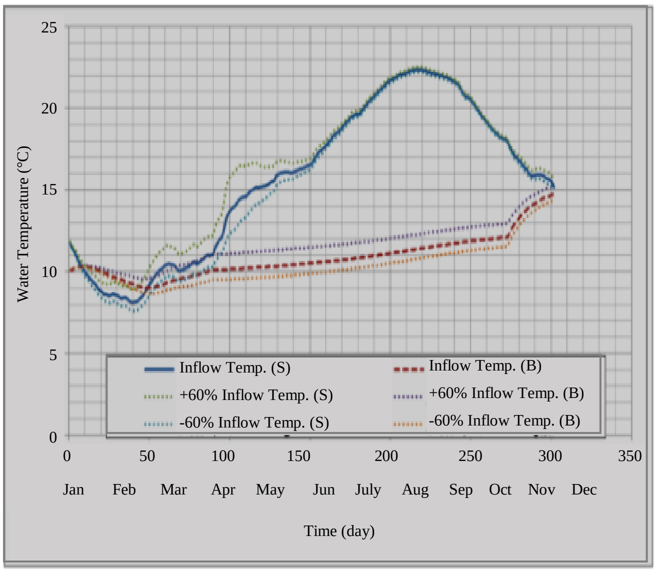

Fig. 7. Sensitivity analysis for the effects due to changes of temperature ofinflow on the reservoir.

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B, B) Analysis of Solar Radiation

The results of sensitivity analysis to determine the effect ofchanges of solar radiation on the temperature of reservoir (surface and bottom layers) are shown in (Fig. 8). The results proved that in the months of January and February, solar radiation has uniformly effect on the water temperature in reservoir. Moreover, by changes in the solar radiation from March to November the surface layer temperature of reservoir has changed from 9 to 16.6°C. In scenarioof 20% decrease in the solar radiation, the simulated results matched the measured profiles well. As the 20% decrease in the solar radiation caused 13.3% decrease in the surface water temperature. In addition, under the case of 20% increase in the solar radiation, the simulated results matched the measured profiles well. The results showed that a 20% increase in the solar radiation causes 13.2% increase in the surface water temperature.

The effects on bottom layer temperature could be seen between March and November (Fig. 8). The results showed that by changes in the solar radiation from March to November the bottom layer temperature of reservoir has changed from 8.1 to 12.1°C. In the case of 20% decrease in the solar radiation, the simulated results matched the measured profiles well. As the 20% decrease in the solar radiation caused 10.3% decrease in the bottom water temperature. In addition, under the case of 20% increase in the solar radiation, the simulated results adequately matched the measured profiles. The results indicated that a 20% increase in the solar radiation causes 10.3% increase in the bottom water temperature.

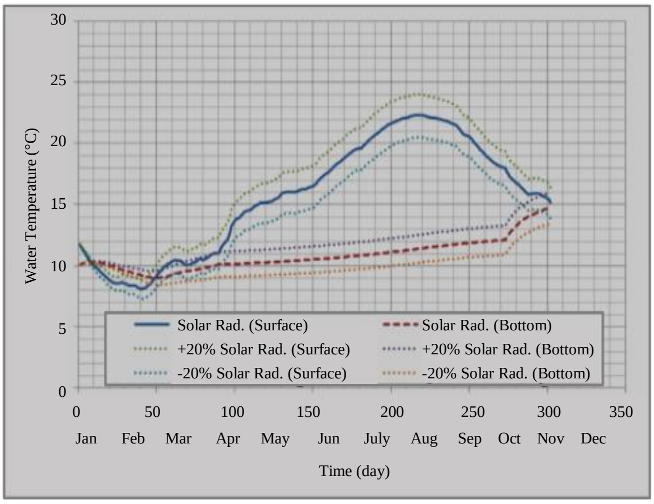

Fig. 8. Sensitivity analysis for the effects due to changes of solar radiation on the reservoir.

The solar radiation was found to be more important parameter affecting the surface water temperature than inflow temperature. Long wave radiation is mostly absorbed or emitted from the surface layer, so it directly affects the surface layer and makes it warm [41]. The results of our analyses indicated that the solar radiation has more effect on surface layer than bottom layer, which are in a good agreement with measured data. Furthermore, the effects of inflow temperature on the reservoir water temperature was less than the effects of solar radiation, which has been proved by earlier studies [41]. The results of our sensitivity analyses showed that the effects of inflow temperature on the surface water temperature are not noticeable. In addition, the effects of inflow temperature on the bottom water temperature were more than surface layer, but they were not comparable with the effects of solar radiation. A summary results of our sensitivity analyses for the effects of changes in the solar radiation and inflow temperature are given in (Table. 2).

Tab. 2. Sensitivity analysis of parameters affecting reservoir temperature

Variable parameter	Changes	Stratifies period	
		Epilimnion	Hypolimnion
Inflow temperature	- 40%	- 10.1%	- 4.76%
	+ 60%	+ 10.6%	+ 7.14%
Solar radiation	- 20%	- 13.3%	- 10.3%
	+ 20%	+ 13.2%	+ 10.3%

Conclusion

A two-layer numerical model was solved with Runge-Kutta method. The influences of inflow temperature and solar radiation in the reservoir temperature were examined by a sensitivity analysis. In the first case the inflow temperature to the reservoir increased by 60% and then decreased by 40%. In the second case ±20% changes of solar radiation was applied to the model. The results showed that the reservoir was stratified approximately during some months in the simulation year.In the months of January, February, March and April, there was no perceptible stratification in the reservoir. On the other hand, in May, June, July, August, and late September there was stratification in reservoir. The solar radiation was found to be more important parameter affecting the surface water temperature than inflow temperature. The results of our analyses indicated that the solar radiation has more effect on surface layer than bottom layer, which are in a good agreement with measured data. The results of our sensitivity analyses showed that the effects of inflow temperature on the surface water temperature are not considerable. Furthermore, the effects of inflow temperature on the bottom water temperature were more than surface layer, but they were not comparable with the effects of solar radiation. Depending on the value of changes employed, the solar radiation caused more than ±13% change in the surface water temperature and more than ±10% change in the bottom water temperature. Moreover, depending on the value of changes employed, the inflow temperature caused less than ±11% change in the surface water temperature and less than ±7% change in the bottom water temperature.

Considering that the heat transfer coefficient between the two layers is assumed to be linear, temperature changes in the bottom layer was linear approximately. Results of modeling showed that the measured values of the error of bottom layer were less than the surface layer, which can have several reasons such as parameters affecting the surface temperature. The results indicated that the stratification could have adverse effects on the Saveh Lake. Since the output water is allocated to drinking purpose, it is prudent necessary measures be taken toreducethe effects of thermal stratification.

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